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FILTERING LOW NOISE AMPLIFIERS FOR SAW-LESS CMOS RECEIVERS

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Abstract. CMOS low noise amplifiers with filtering capability represent an exotic class of LNAs offering the opportunity for RF designers to minimize their design by avoiding the SAW passive filters. Thought as a state of the art, the paper reviews the most outstanding architectures proposed in the literature, trying to offer some insight on designing bandpass LNAs envisaging SAW-less receivers.

Key words: bandpass; CMOS; LNA; notch filters; SAW.

1. Introduction

The continuous development of the CMOS technology during the last two decades opened the path to the proliferation of low-cost, low-power and low-chip area multi-mode mobile terminals. Thus, the CMOS process developed from 3 µm (analog) (Wang & Abidi, 1990)/1.2 µm (digital) (Steyaert *et al.*, 1990) to 32 nm (analog and digital) (Lakdawala *et al.*, 2013) CMOS process. This process scaling (Mazor, 2009), truly predicted by the Moore law (Moore, 1965), favoured the implementation of different 2*G*/3*G* wireless transceivers, analog and digital parts, into a single chip, entirely designed in CMOS process. However, on the RF side, three external blocks still represent a major issue in implementing a fully integrated RF front-end: the antenna

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duplexer (Omer *et al.*, 2012; Fischerauer *et al.*, 2001), preselective and image rejection SAW filters. Using all three or some of them only depends on the particular channel access method implemented at the OSI physical level (transceiver architecture in particular). Thus, in case of WCDMA systems which use an FDD (frequency division duplex) access scheme, as implemented by MAX2390 (www.maxim-ic.com) (shown in Fig. 1) for the GSM1900 downlink bandwidth, transmitting and receiving between user and base station occurs simultaneously at distinct frequency channels. This imposes to the antenna duplexer, a three port duplexer filter connecting the antenna either to receiver or transmitter, to allow bi-directional communication (duplex). This is the reason why the duplexer must isolate enough the transmitter and receiver paths during the communication. If the duplexer does not offer sufficient Tx leakage rejection, the spurious Tx signal will cause severe dynamic range and intermodulation problems in the receiver chain. As reported by Sowlati *et al.* (2009), a duplex isolation of 53 dB causes for 24 dBm transmitted power a degradation of NF with 0.6 dB.

In the case of telecommunications networks using TDD access scheme, as implemented by MAX2392 (www.maxim-ic.com) (Fig. 1), proposed for UMTS networks in China (as alternative to WCDMA (TD-SCDMA, 2004)), the same frequency band is used by both transmitter and receiver. In this case, the duplexer mainly consists of a switch, connecting the receiver or transmitter to antenna in particular time slots.

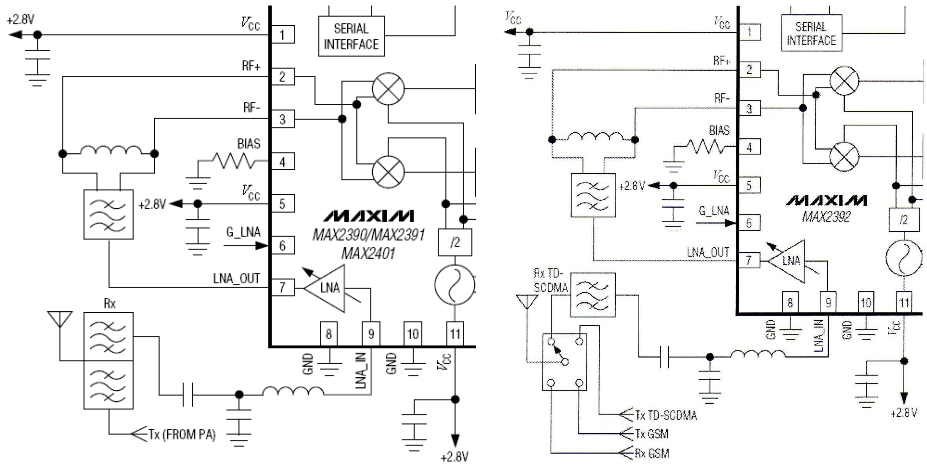

Fig. 1 – MAX2390 FDD W-CDMA Band II (1930-1990 MHz) and MAX2392 TD-SCDMA (2010-2025 MHz, TDD) receivers.

As noticed in Fig. 1, supplementary RF filters are required for normal operation, currently SAW devices being used for RF filtering, this technology clearly dominating the telecommunications market over the last two decades (www.epcos.com; www.triquint.com). However, the architectures shown in

Fig. 1 are single standard only while most mobile phones existent on the market are dual-mode (2*G* and 3*G*) multi-standard devices, being in most cases penta-band 2*G*/3*G* (850/900/1800/1900/2100) and offering Bluetooth connectivity, WIFI access (WLAN *a*/*b*/*g*/*n*) and GPS navigation. If using two filters might not constitute a problem when implementing one standard only, it raises many problems for multi-standard devices, containing at least 4…6 filters, as shown in Fig. 2 (http://us.fujitsu.com/micro), since the SAW filters are external, bulky and offer no frequency tuning possibility, charging more the mobile users.

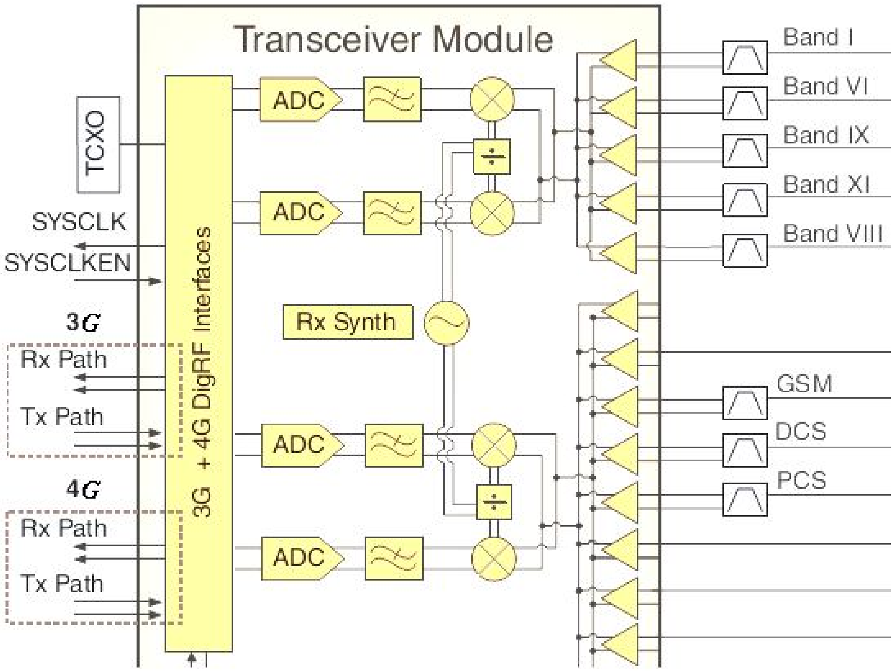

Fig. 2 – Fujitsu MB86L10A 2G/3G/LTE multimode multi-band transceiver.

However, placing a bank of SAW preselective filters at the multi-standard receiver input is the most common solution in practical implementations. This is the reason why extensive research has been devoted to find out solutions for avoiding the SAW filters, if possible. Avoiding SAW filters depends on the particular topology of the RF transceiver and the standard specifications, more relaxed filter constraints allowing the implementation of active solutions. In this regard, different active approaches have been proposed in the literature to replace either the preselective filter or the image rejection one. Since the LNA is in between the SAW filtering devices, most of these active solutions envisage also the LNA design. Solutions dealing with the first preselective RF filter are discussed in following section, low noise amplifiers allowing the implementation of SAW-less receivers being reviewed. Conclusions are drawn in section **3**.

2. Blocker Filtering Techniques

Blockers are either out-of-band signals with sufficient power level to saturate the receiver front-end (thus reducing the receiver gain and increasing the noise contribution of the stages after the LNA) or strong in-band signals that can desensitize the receiver. A technique to deal with in-band blockers is discussed by Tadjpour *et al.* (2001). However, while the problem of in-band blockers can be easily solved in current transceivers through baseband filtering, the out-of-band blockers can be rejected through front-end filtering only. Therefore, a supplementary SAW preselective filter is usually be inserted after the duplexer in Fig. 1 (as already shown in Fig. 2) in order to attenuate the Tx residual leakage and other blockers, thereby relaxing the linearity requirements of the Rx chain. Since the SAW filters are the first block on the RF path (after antenna) and have no gain, the final cost and chip-area are increased while the noise figure is degraded. In addition, such filters have no frequency tuning capability, therefore being unattractive in software defined radios (SDR). In this regard, several interesting active solutions have been proposed in literature during the last years to replace or avoid the SAW filters. The basic idea is to move the filtering operation at the LNA level so that the input signal filtering and amplification are implemented simultaneously.

One first solution is to move the preselective filtering after the LNA and implementing it actively (Zhiqiang Gao *et al.*, 2008), as shown in Fig. 3. The basic idea is that the filtering-LNA (Fig. 3 *b*) can fulfill the standard requirements (mainly on linearity and noise) for Bluetooth, WiFi and other telecommunications standards, in case that the multi-band RF filter has a minimum gain of 5 dB and noise figure less than 20 dB. The tuning possibility is only achieved by using transistor only simulated inductors (TOSI), a single TOSI being sufficient to implement a second order RF filter. The architecture reported by Zhiqiang Gao *et al.* (2008) and detailed later (Zhiqiang Gao *et al.*, 2010) (Fig. 4) has B_{3dB} = 60 MHz, G = 6 dB and NF = 18 dB.

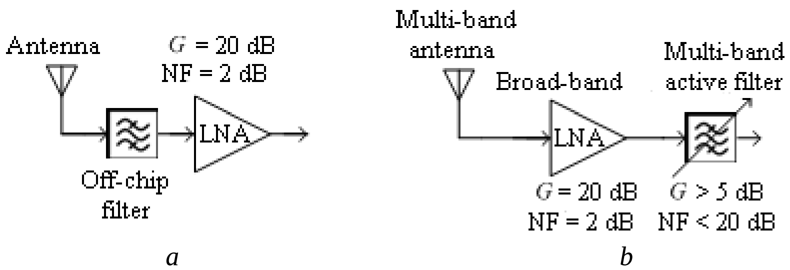

Fig. 3 – Multiband RF front-end design, typical (*a*) and proposed (*b*) (Zhiqiang Gao *et al.*, 2008).

Using negative resistances ($M_7,\ldots,M_{10}$) allows for (center) frequency and quality factor (or bandwidth) tuning. Yet, reported to the SAW passive solution, the price is increased noise (due to simulated inductors) and power consumption. In addition, careful design must be applied in order to make the circuit as linear as possible. However, depending on the active inductor topology, the thermal noise may be minimized, as proposed by Krishnamurthy *et al.* (2010), for a gyrator implemented with differential transconductors. In this case, a bandpass filter with high gain (G = 20...33 dB) and low noise factor (NF = 5 dB) is reported. Such structure suits well the solution proposed by Zhiqiang Gao *et al.* (2008), being able to cover the UWB frequencies, as well.

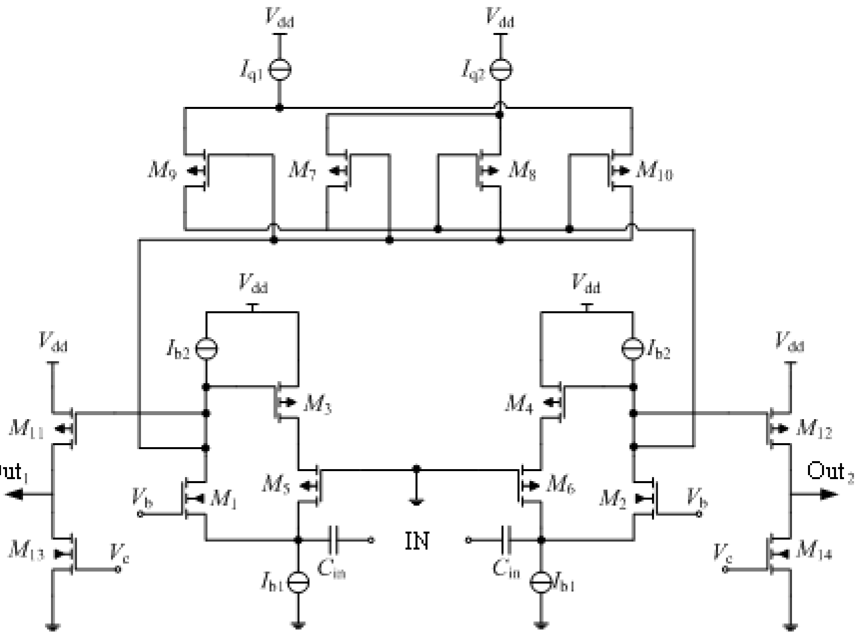

Fig. 4 – TOSI based multiband RF filter (Zhiqiang Gao *et al.*, 2008).

Using active inductors is not a novel idea, an attempt to implement a fully active RF preselective filter, implemented in CMOS process and envisaging UWB applications being already reported in the literature (Heesong *et al.*, 2005). This was a pseudo-passive filter, containing two capacitive coupled *LC* resonators implemented with TOSI inductors. However, the high noise figure reported for this topology (NF = 14 dB) makes it unattractive either as preselective filter or after the LNA as in Fig. 3 (having no gain). To some extent, this solution was similar to other two TOSI based RF filters reported by Thanachayanont (2002) and Yue Wu *et al.* (2003).

An elegant solution, depicted in Fig. 5, consists in amplifying the same RF input signal on two paths while rejecting the bandwidth of interest on one path by means of a notch filter. By subtracting the signals at the output, the bandwidth of interest only is obtained, the entire scheme acting like a bandpass filter. The practical implementation is shown in Fig. 6. For this circuit, the first path is defined as M_1-M_3-M_4, containing the notch filter (L_f, C_f), while the second one is represented by M_2 only. Since M_1 and M_4 are inverters, the signal flowing on the first path appears not inverted at the output, while M_2 inverts the same input signal. Thus, at the common drain of M_2 and M_4, these two signals are subtracted. The scheme is sufficient simple and easy to implement, therefore being suitable for RF design.

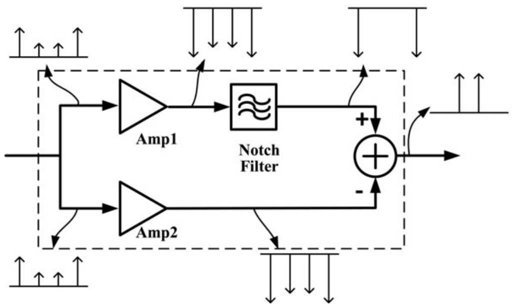

Fig. 5 – Blocker filtering LNA (Heesong *et al.*, 2009).

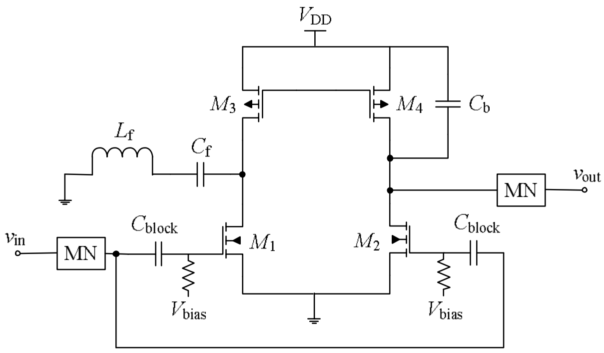

Fig. 6 – Blocker filtering LNA for 2.4 GHz ISM band (Heesong *et al.*, 2009).

As can be noticed, the power consumption is kept as minimum as possible, the circuit containing in fact a single differential stage. As reported in the cited paper, a low noise figure of 1.85 dB is achieved together with attenuations of –13 dBc and –29 dBc at –400 MHz and 400 MHz apart.

The main drawback of this topology is using external matching networks, the discrete devices having large tolerance. In addition, the on-chip inductors require large area, therefore increasing the overall chip area. Finally, this circuit has no freedom degrees since its frequency selectivity is set by the on-chip inductor quality factor only. However, such bandpass filtering LNA suits well the telecommunications standards which do not impose steep attenuations.

As could be noticed, the previous method consists in filtering the out-of-band signals directly in the RF domain, a difficult task for RF designers. In fact, the reason of using SAW filters is the impossibility of implementing a good active bandpass filter (including low NF) at 1…2 GHz or higher frequencies. However, there is another possibility, interesting too. In this case, the RF input signal is filtered at lower frequencies (intermediate frequency), after being moved from higher frequencies with a supplementary mixer on the feed-forward path, as proposed by Darabi (2007) (Fig. 7).

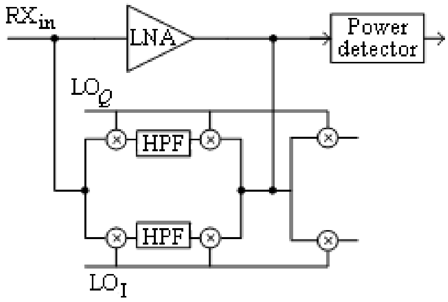

Fig. 7 – Blocker filtering LNA for 1.9 GHz GSM band (Darabi, 2007).

This technique is pretty similar with the first one, a replica of the input signal, containing the blocker and not the bandwidth of interest, being subtracted at the output. The single difference is that the filtering process is done in this case at lower frequencies (at an intermediate frequency). This method was applied to design a SAW-less receiver for PCS standard (1,930…1,990 MHz). The LNA is a differential common gate amplifier, with cascode stage and parallel *LC* load using capacitor array. Since a high order filter with steep attenuation is much easier to be implemented at lower frequencies, this method offers better results than the previous one. The single requirement is that the low frequency notch filter must be sharp enough to let the blocker pass. However, this method has also drawbacks since its performance depends on gain and phase match between the main and auxiliary path. Thus, the phase match is of greatest importance and in the same time directly depends on the frequency performance of both mixers and phase shift of the HPF. In addition, since the subtraction is implemented at the output, the LNA must be able to tolerate large signals (the blockers). In this regard, the common gate amplifier is the best choice since it has no gain at the input, therefore is less affected by large blockers.

A similar technique, less sensitive to mismatches thanks to using a notch filter centered at a frequency of $2f_{LO}$, was proposed by Abouzied *et al.* (2010). Designed at 2 GHz, the filtering LNA offers a rejection of more than 15 dB in a bandwidth of ±500 MHz, which is not so much compared with the stringent requirements of 2*G*/3*G* standards. However, it is a good solution for more relaxed telecommunications standards.

A mixing between the methods proposed by Zhiqiang Gao *et al.* (2008) and Darabi (2007) was reported by Werth *et al.* (2010). In other words, the idea is to have an LNA that allows large blockers and an *LC* tank together with an active feedback interference cancellation (Fig. 8). According to the calculus illustrated in the same paper, comparison with the classical receiver with SAW preselective filter being presented too, such SAW-less receiver achieves a better reference sensitivity as insertion loss preceding the LNA is minimized.

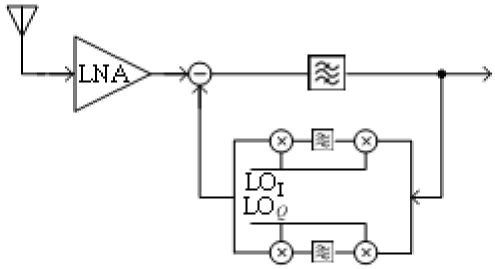

Fig. 8 – SAW-less DCR with active feedback interference cancellation (Werth, 2010).

An alternative for the method depicted in Fig. 7 was proposed by Izquierdo *et al.* (2010). In this case, the blocker is rejected at the LNA input, as depicted in Fig. 9. Such operation is done by inserting a feedback chain composed from a filter, up-conversion mixer and transconductance amplifier (OTA). Since the receiver input impedance (Z_{in}) depends on the LNA input impedance ($Z_{in,LNA}$) and the feedback loop, the main idea in this case is to create

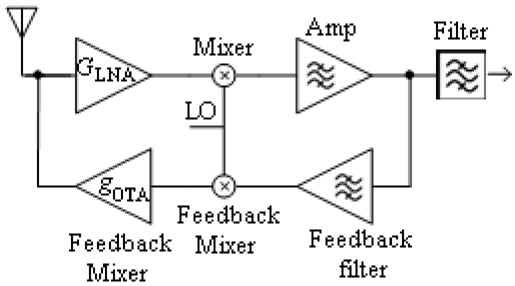

Fig. 9 – BB-RF-FBRX receiver (Izquierdo *et al.*, 2010).

a mismatch at out-of-band frequencies, while matching the LNA within the band of interest. Such receiver was called *base-band to radio-frequency feedback receiver* or BB-RF-FBRX. Details on design optimization, mainly regarding the noise, stability and feedback loop components, are presented in the same cited paper. The same idea of filtering out the energy of out-of-band frequencies was reiterated by Chi-Yao Yu *et al.* (2011), where the LNA (Fig. 10) plays the role of an LNTA (low-noise transconductance amplifier). The LNA particularity is that the input transistors, $M_{1,2}$, are biased in weak inversion, therefore making it suitable for low power applications together with achieving very low noise figure (NF = 1.4 dB). The LNA is followed by passive mixers – implemented with blocker detection stage (for LO power reduction) – and a transimpedance amplifier (TIA). All together supplement the function of the SAW preselective filter so that it is no longer necessary.

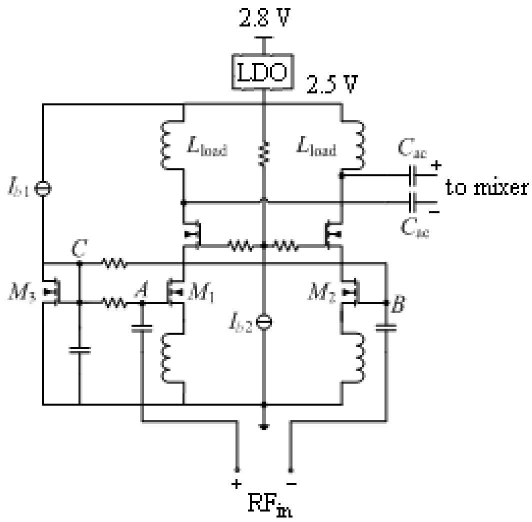

Fig. 10 – LNTA schematic (Chi-Yao Yu *et al.*, 2011).

Another solution envisaging the GPS L1 applications (f_0 = 1,575.42 MHz) was proposed by Barth *et al.* (2011). The filtering amplifier has a bandwidth of less than 12 MHz and exhibits a steep roll-off characteristic, achieving more than 30 dB attenuation at frequencies greater than 30 MHz away from the center frequency. Thus, such a topology is capable to achieve the performances of the SAW filters dedicated to GPS applications and might be use in SAW-less GPS receivers which usually contain a SAW preselective filter (Xin He & van Sinderen, 2009), as shown in Fig. 1. In Fig. 11, the LNA is a classical cascode source degenerated common source amplifier, in differential

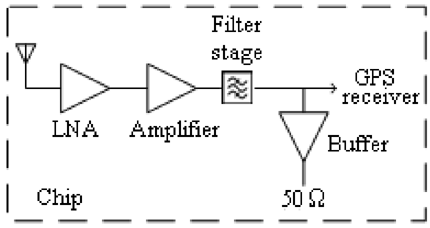

Fig. 11 – Double notch filter for GPS SAW-less receivers (Barth *et al.*, 2011).

topology and loaded by a parallel *LC* resonator, tuned to the GPS L1 center frequency (1,575.42 MHz). It provides a gain of 18 dB, sufficient to overcome the noise of the following active stages. A second amplifier is inserted in order to increase the overall gain, providing an extra gain of 7 dB. This is a simple differential amplifier with resistive load, followed by source follower buffer stages, needed to drive the capacitance of the input transistors of the filter stage. The filter architecture is shown in Fig. 12, together with the notch structure which is used as NS1 (with C_1-L_1-C_2, V_{tune1}, I_{gm1}) and NS2 (with C_3-L_2-C_4, V_{tune2}, I_{gm2}). I_{gm1} and I_{gm2} control the filter bandwidth while the negative resistance (M_p, M_n) is used to increase the quality factor of on-chip inductors (usually between 5 and 10). In the same figure, M_1-M_2-NS1 constitute the filter transconductance while M_3-M_4-L_3-NS2, the filter transimpedance.

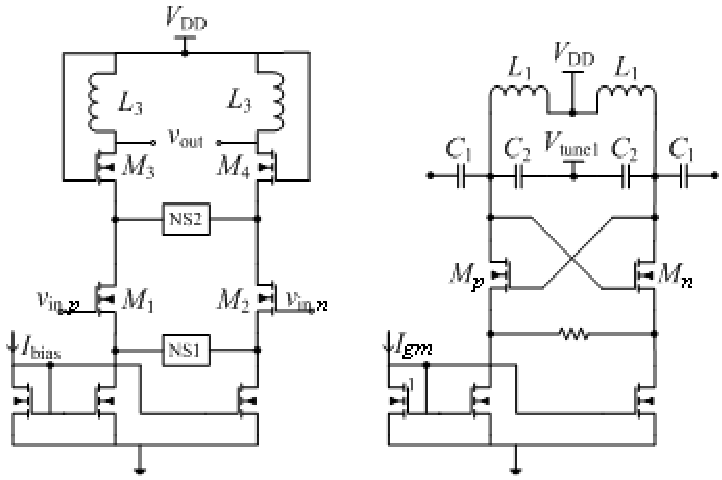

Fig. 12 – Filter architecture and notch stage (NS) structure (Barth *et al.*, 2011).

3. Conclusions

The most outstanding contributions on the practical implementation of filtering low noise amplifiers envisaging SAW-less receivers were reviewed in this paper. Historically speaking, this exotic class of low noise amplifiers can be considered as corresponding to the third stage, the first one referring to classical single standard LNAs and the second grouping the multi-band/multi-standard LNA. However, the evolution of LNAs is not dissociable of the RF front-end development and, as some novel references published during the last two years show, it is likely that LNA together with the SAW filter will be avoided, the first RF part becoming even the passive mixers. Until then, all LNAs reviewed in this paper constitute good solutions for particular standards and applications.

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AMPLIFICATOARE FILTRANTE CU ZGOMOT MIC PENTRU RECEPTOARE CMOS FĂRĂ FILTRE SAW

(Rezumat)

Amplificatoarele CMOS cu zgomot mic, având capacitatea de filtrare, reprezintă o clasă exotică de LNA-uri care oferă oportunitatea proiectanților de circuite de a-şi minimiza design-ul prin evitarea utilizării filtrelor pasive de tip SAW. Gândit ca un „state of the art” în domeniu, lucrarea rezumă cele mai notabile arhitecturi propuse în literatură, încercând să ofere un „background” cu privire la proiectarea LNA-urilor de tip trece bandă şi vizând receptoarele fără filtre SAW.